The Primary Pattern Generator Part IV–Alignment and Performance Evaluation

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I. REQUIREMENT FOR ALIGNMENT

The mechanical nature of the primary pattern generator (PPG) requires a precise juxtaposition of most of the machine elements in order to achieve both pattern accuracy and reliable functioning of the machine. Part II described the alignment of the rotating polygonal mirror to the air-bearing axis. The precision required in that assembly is the tightest tolerance in the PPG. This precision is required to produce a uniform scan-line spacing on the pattern. In addition, the direction of that scan line must be made as perpendicular as possible to the travel direction of the photographic plate. Therefore, the carriage of the photographic plate must move without rotation. The method for aligning the polygonal mirror axis to the carriage direction will be described, as well as other alignment needed to produce an accurate pattern. The code-plate system for controlling the fast scan was described in Parts I and III. Implicit in this description was the assumption that the code-plate grating and the photographic plate are the exact same distance from the scanning lens (see Fig. 1 in Ref 1). The positioning of the code plate to achieve accurate length of the fast scan is a critical alignment that requires a combination of optical and electronic techniques.

The accuracy goal for the PPG was 100 parts per million (ppm) deviation from an absolute coordinate system, the error reference being the overall dimension of the full PPG field. Thus the coordinate axes of the pattern must be othogonal to within 20 seconds. A second of arc is approximately 5×10^{-6} rad. The photographic-plate position is determined by a lead screw as described in Part II. The accuracy of this

screw is the determining factor in the overall length error of the plate translation axis. For convenience, we will refer to this axis as the Y-axis and the fast scan axis as tbe X-axis.

The functional alignment includes positioning the optical modulator, obtaining separation of the coding and writing beams, positioning of the scanning lens, and positioning of various other lenses and mirrors in the optical paths of tbe two beams. The design and alignment of the laser cavity is described. The long-term functioning of the PPG will require replacement of the laser discharge tubes. Our design-and-alignment procedure allows tube replacement without realignment of the remainder of the optics.

II. FUNCTIONAL ALIGNMENT

The quartz laser tube is clad with a water-cooling jacket and is rigidly mounted within a solenoid which provides the axial magnetic field. By placement against pins, tbis assembly is located precisely on a flat plate on which the cavity mirrors are rigidly mounted. This system was devised so that a remotely located reference cavity can be used to prealign a laser-tube-solenoid assembly to the laser cavity on the PPG. The use of the reference cavity significantly reduces the down time of the PPG during laser replacement; replacement of the laser does not require realignment of the PPG.

The laser cavity is of a nearly hemispherical configuration consisting of a 0.9-m radius highly reflecting mirror and a flat, transmission mirror at the output. The separation is 0.75 m. The output is constrained to the TEM_{00} mode by using a 2-mm aperture inside the cavity near the spherical mirror. The 514.5-nm line is selected by the transmission characteristic of the output mirror.* The output mode of the laser has a $1/\epsilon$-amplitude radius[2] of 200 μm. The train of lenses and mirrors (see Parts I and II) whicb is used to direct the laser output to the optical modulator was aligned by autoreflection at each mirror. The lenses were inserted after the beam had been correctly positioned. Back reflections from each lens were used to center accurately that lens.

The optical modulator must be positioned to the Bragg angle.[3] The angle is set by periodically exciting the modulator and then detecting the deflected beam with a photodetector and maximizing the modulation. After the modulator is positioned, the writing-beam separation

* The reflective band of the transmission mirror is centered near 550-nm wavelength. The edge of the band is at 514.5 nm and thus the reflectivity at all the other spectral lines is insufficient for oscillation.

mirror (see Part I) is positioned. A 10-cm focal length lens placed at the modulator output produces the required spatial separation of the writing and coding beams. At the separation mirror each beam has a $1/\epsilon$-amplitude radius of 50 μm and the center-to-center beam spacing is 400 μm. At this location, the coding beam is 20 to 50 times the intensity of the writing beam. The light from the coding beam which is scattered in the writing beam direction is removed by an 0.75-mm aperture placed concentric with the writing beam. Slight tilting of lenses eliminates objectionable back reflections. After these adjustments, the on-off ratio of the writing beam is greater than 50.

III. ACCURACY ALIGNMENT

The path of the writing beam from the modulator to the scanning lens (see Fig. 1 of Ref. 1) is determined by three adjustable mirrors in addition to the writing beam separation mirror. These three mirrors are used to properly direct the writing beam into the scanning lens. However, the proper position of the scanning lens is determined partly by the positions of the rotating mirror and photographic plate. Consequently, the rotating mirror must first be aligned to the photographic plate; then the writing-beam illumination of the scanning lens can be set and finally the scanning lens is positioned.

The alignment between the rotating polygonal mirror and the translational direction of the photographic plate (Y-axis) is accomplished by use of a precision cube and an autocollimator. The cube is mounted on the photographic-plate carriage in such fashion that a cube face is normal to the Y-axis. Errors are introduced by the yaw, pitch and roll of the carriage; each contributes a few arc seconds of error. First, two faces of the cube are indicated parallel to the Y-axis by using sensors capable of detecting $\frac{1}{40}$ μm displacement. The cube face normal to these two faces is normal to the Y-axis. The X-axis of the pattern is the intersection of a plane normal to the axis of rotation of the polygonal mirror (this plane is also normal to all of the facets of this mirror) and the plane of the photographic plate. The plane of the photographic plate must be parallel to the Y-axis or else the X-axis as defined above will not always be in the focal plane of the scanning lens. A sufficient, but not necessary condition for the X-axis to be normal to the Y-axis is to make the carriage travel direction parallel to the rotation axis of the polygonal mirror. This is accomplished by using an autocollimator to set the reference face of the polygonal mirror (the reference face is perpendicular to all the facets of the mirror) parallel to the face of the precision cube which is normal to the Y-axis.

The actual angle between the X- and Y-axes was determined by generating a test pattern on the PPG and measuring this pattern with a coordinate-measuring machine (CMM).[4] This measuerement could be made with an error of less than 3 s. Thus, a correction to the direction of the rotating mirror was determined and used to reset the X-axis. Since this correction was less than 20 s, no other alignment was disturbed.

After the initial positioning of the rotating-mirror axis, the writing beam must be directed to the center of the entrance pupil of the scanning lens. This is set by autoreflecting the writing beam from a properly positioned polygonal mirror facet. The proper angle of the facet is calculated from the parameters of the scanning lens. The polygonal mirror facet is exactly positioned by the use of an autocollimating theodolite. The position which must be taken by the axis of the scanning lens is now fully constrained. This position is duplicated by a helium-neon laser beam which is positioned normal to a facet of the polygonal mirror. This facet is first set parallel to the X-axis. The He-Ne laser beam is also passed through the center of the scan line on the photographic plate. The scanning lens is positioned by centering its back reflections of the He-Ne laser beam thereby aligning the axis of the scanning lens with the He-Ne laser beam.

The last step in the X-axis alignment is the length-accuracy adjustment of the code-plate position. To accomplish this, a replica of the code-plate grating is produced by contact printing onto a photographic plate. This plate is then positioned in the PPG in exactly the manner a photographic plate is positioned when it is to be exposed. A long, silicon PIN photodetector is placed under the replica grating. The focused writing beam will produce a signal output from the PIN photodetector as it sweeps across the replica grating. However, the long photodetector has very little bandwidth. To circumvent this photodetector deficiency, the output of the actual code plate is used to modulate the writing beam by feeding the code plate signal into the optical modulator. Now the long photodetector under the replica grating will only have to respond to the beat frequency between the code-plate signal and the writing beam sweeping the replica. By adjusting the beat frequency to zero throughout the scan, the exact position registration between writing and coding beams is obtained. This method of alignment resulted in less than 10-ppm error in the X-axis length. Residual errors are caused by camber of the photographic plates (see Part I), inevitable temperature variations, and camber in the coding-beam output mirror (see Fig. 1 of Ref 1).

IV. PERFORMANCE EVALUATION

The design and fabrication of the necessary high-frequency mechanical components allowed the synchronization between the fast scan and the photographic-plate translation to be accomplished by a simple, computer-controlled system. Further, this step-on-command system allows flexibility in the computer control so that future work can produce a more economical division of work between the PPG control computer and the PPG postprocessor.[5] At present, very few of the patterns drawn by the PPG have required the machine to wait for the computer to finish assembly of a line.

The rotating mirror presented the most critical item in terms of tolerance. The periodic bunching and spreading of the scan lines caused by the nonideal mirror results in both a periodic variation in the optical density of exposed regions and a periodic displacement in feature edges which are parallel to the Y-axis. The optical density variation is lost when the pattern is photographed by the reduction cameras. However, the periodic displacement is still detectable after the first reduction; the peak-to-peak amplitude is less than one-third address.

The major inaccuracy in the PPG is the Y-axis length. The lead screws used are accurate to within 15 ppm at 20°C. However, the lead-screw temperature in the operating machine is 25°C and so the Y-axis length is in error by 90 to 100 ppm. However, the lead screws can be replaced and this error can be eliminated.

The measured reproducibility of the PPG cannot be separated from the reproducibility of the coordinate-measuring machine. It was found that remeasurement of a PPG plate on the CMM produced readings which showed a variance of one-third address at the extremes of the pattern field. Near the CMM reference point in the pattern, the variance of the readings was approximately one-sixth address.[4] Such behavior indicates a systematic error such as that caused by temperature differences. If the reproducibility of the CMM is accounted for, the variance in the location of a PPG-produced feature is not greater than one-third address and may be less than one-fourth address. Figure 1 shows the measured scatter of identical features drawn on 18 separate plates made over a period of two months. The (X, Y) address location of the CMM reference was (1000,1375) in the PPG field. The scale on the axes of the scatter plots are in addresses with respect to the absolute coordinate. Note the error increase in Y caused by the excess length of the Y-axis.

The PPG, as constructed, meets all of the requirements set by the mask-making system.[6]

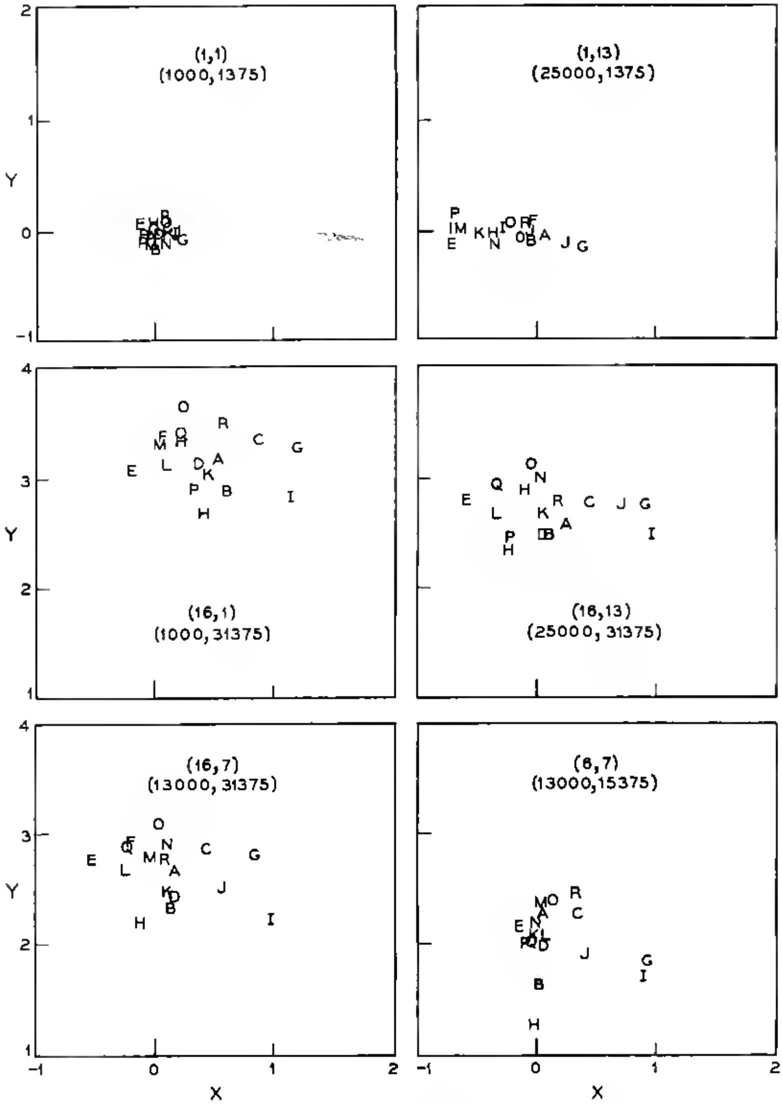

Fig. 1—Reproducibility of pattern generator.

V. ACKNOWLEDGMENT

A. D. White computed the illumination angle for the scanning lens.

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